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Cost and Performance Report

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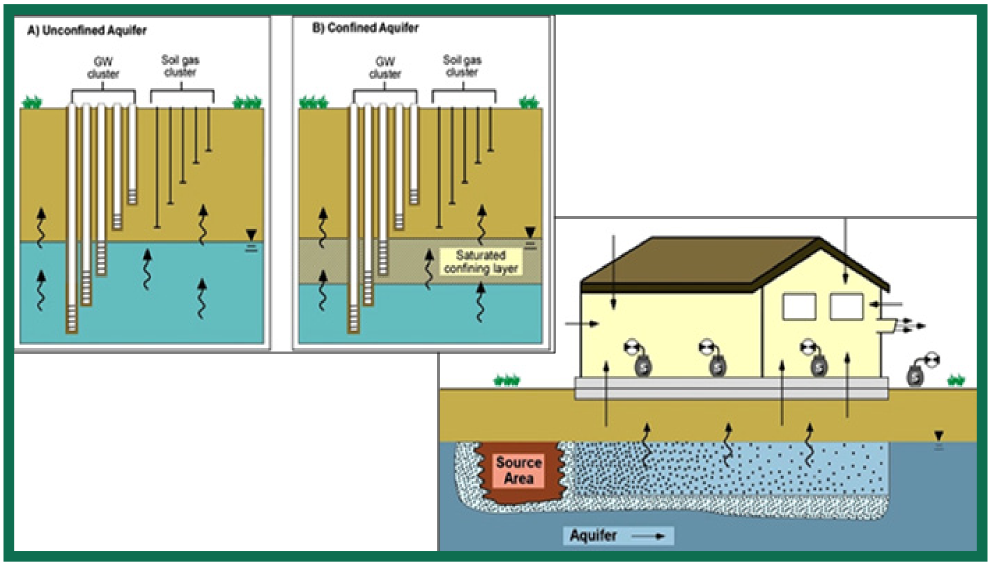

Proposed Tier 2 Screening Criteria and Tier 3 Field Procedures for Evaluation of Vapor Intrusion

August 2012

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ACRONYMS AND ABBREVIATIONS

1,1-DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethene
1,1,1-TCA	1,1,1-trichloroethane
1,1,2-TCA	1,1,2-trichloroethane
AF	attenuation factor
AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
ANOVA	Analysis of Variance
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
ASU	Arizona State University
bgs	below ground surface
COC	chemical of concern
DCE	dichloroethene
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
ETV	Environmental Technology Verification
GC	gas chromatography
HGL	HydroGeoLogic, Inc.
ITRC	Interstate Technology and Regulatory Council
MS	mass spectrometry
NA	not applicable
NAS	Naval Air Station
NIOSH	National Institute for Occupational Safety and Health
NJDEP	New Jersey Department of Environmental Protection
NM	no measurement
NYDOH	New York Department of Health
OTC	Old Town Campus
Pa	Pascal
PCA	1,1,2,2-tetrachloroethane
PCE	tetrachloroethene
QAPP	Quality Assurance Project Plan

ACRONYMS AND ABBREVIATIONS (continued)

SF_6	sulfur hexafluoride
SPAWAR	Space and Naval Warfare Systems Command
TCE	trichloroethene
USEPA	U.S. Environmental Protection Agency
VC	vinyl chloride
VI	vapor intrusion
VOC	volatile organic compound

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

It is estimated that more than 7000 Department of Defense (DoD) sites have contaminated groundwater, most of which will require investigation of the vapor intrusion (VI) pathway. Although screening criteria are available and accepted in many other types of investigation and regulatory contexts, the VI pathway is relatively new. As a result, screening criteria tend to be extremely conservative, "prioritizing" the majority of sites for further investigation.

The overall objective of this project was to develop and validate simple procedures to screen for VI and provide criteria for decision making, including no further need for site evaluation for the VI pathway. The procedures rely on easily-obtainable site-specific information that can be applied to criteria that are protective but less conservative than the generic (i.e., Tier 1) screening concentrations provided in many U.S. Environmental Protection Agency (USEPA) and state VI guidance documents.

For this project, two methods were developed and evaluated: 1) Tier 2-level, site-specific evaluation and screening based on physical properties such as soil type and 2) building-specific Tier 3 field investigation of the VI pathway based on building characteristics. Performance objectives included collecting data from multiple sites in a consistent and comparable manner to allow evaluation of factors influencing volatile organic compound (VOC) migration and attenuation. The performance objectives were met by collecting and analyzing data at seven sites for the Tier 2 evaluation and six sites for the Tier 3 evaluation.

1.2 TECHNOLOGY DESCRIPTION

The Tier 2 and 3 procedures were based on the results obtained from Environmental Security Technology Certification Program (ESTCP) Project ER-200423, Detailed Field Investigation of Vapor Intrusion Processes (GSI, 2008a). The demonstrations for Tier 2 and Tier 3 evaluation methods included:

- <u>For Tier 2</u>: 1) field and laboratory measurements of soil characteristics to determine the best method for identification of sites with fine-grained soils within 2 ft above the water table and 2) detailed VOC concentration measurements in groundwater and soil gas to evaluate vertical profiles and VOC attenuation. The demonstration program yielded groundwater to deep soil gas attenuation factors for seven sites covering a range of soil characteristics allowing validation of the hypothesis that VOC attenuation is higher at sites with fine-grained soils within 2 ft above the water table.
- <u>For Tier 3</u>: 1) control of building pressure to create negative and then positive building pressure conditions; 2) measurement of pressure gradients across the building envelope and building foundation; and 3) measurement of radon, indoor tracer gas, and VOC concentrations in indoor air and sub-slab soil gas under each pressure condition. The results of the demonstration program allowed an evaluation of 1) building foundation permeability based on measurement of cross-

foundation pressure gradients, 2) the effect of building pressure control on the movement of soil gas into buildings, and 3) the utility of sampling under controlled building pressure conditions to evaluate VI.

1.3 DEMONSTRATION RESULTS

The field investigation program for Tier 2 evaluated the importance of factors such as soil permeability, hydraulic conductivity, soil moisture, and grain size in VOC attenuation. Based on the results of the demonstration program:

- We recommend that groundwater screening concentrations at fine-grained soil sites be increased by 100H over the default (i.e., Tier 1) screening values determined to be protective for all types of sites, subject to limitations described in the Implementation Issues section below.
- For identification of fine-grained soil sites, field-measured soil (intrinsic) permeability at depths within 2 ft above the water table was found to be the most accurate method. Visual inspection of soil cores also provided an accurate soil type classification at six of seven demonstration sites.

The field investigation program for Tier 3 demonstrated that a building-specific investigation program utilizing sampling under controlled building pressure conditions provides an improved understanding of the potential for VI in the building:

- Controlled negative building pressure supported the flow of soil gas into the building, as documented by increased indoor concentrations of radon and VOCs originating from subsurface sources. Conversely, controlled positive building pressure suppressed the flow of soil gas into the building, as documented by radon concentrations in indoor air equal to the concentration in ambient air. The response of VOCs originating from the subsurface was similar to radon. In contrast, the indoor air concentration of VOCs originating from aboveground sources showed little difference between the induced pressure conditions.
- An expanded version of the Tier 3 demonstration program implemented in two buildings demonstrated reproducibility of the procedure.

In one building, VI was not evident during initial baseline sampling but was induced under negative pressure conditions. This finding is consistent with other studies, which have shown episodic VI in this building. The results from this building demonstrate that the Tier 3 investigation procedure reduces the uncertainty associated with temporal variability in VI.

1.4 IMPLEMENTATION ISSUES

The Tier 2 screening procedures will be useful only at certain sites (i.e., sites with fine-grained soil layers within 2 ft above the water table. Sites with exclusively sandy soils and sites in dry climates with low moisture content soils will not benefit). The Tier 2 screening procedure should not be applied to sites where the depth to groundwater is less than 5 ft below ground surface (bgs).

The Tier 3 procedure is not applicable to very large or very leaky buildings where the building pressure cannot be easily controlled. In addition, the pressure control method does not eliminate the spatial variability on VOC concentrations that is observed at many investigation sites. Results showing that VI occurs only under depressurized conditions will not be directly applicable to normal building operating conditions because the observed magnitude of VI under these conditions may be greater than under normal operating conditions. In these cases, the investigator may choose either preemptive mitigation or continued monitoring.

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2.0 INTRODUCTION

2.1 BACKGROUND

Since 2000, regulators and the regulated community have become increasingly concerned about the potential for exposure to VOCs through VI to indoor air at sites with contaminated soil or groundwater. Relatively few VI case studies are available in published literature (e.g., Folkes et al., 2009; Eklund and Simon, 2007; DiGiulio et al., 2006; Sanders and Hers, 2006). However, detailed investigations at a limited number of corrective action sites have documented elevated levels of chlorinated VOCs in houses located above contaminated groundwater (Tillman and Weaver, 2005; DiGiulio et al., 2006). In response, USEPA and many state regulatory agencies have issued guidance specifying screening and field investigation procedures for the identification of VI impacts at corrective action sites. Although the specific recommended investigation procedures vary significantly between guidance documents, the majority of these documents utilize a step-wise evaluation process that includes preliminary screening followed by field investigation, if needed. Of the available regulatory guidance on VI, the USEPA guidance (USEPA, 2002) is currently the most widely applied. This guidance document has been formally adopted by some states (e.g., Ohio) and is also widely used in states that have not issued their own guidance documents. The USEPA VI guidance recommends the following step-wise evaluation approach:

1. <u>Check for presence of volatile chemicals</u>: VI is a potential concern at sites with soil or groundwater impacted by volatile chemicals, typically defined by vapor pressure or Henry's Law constant.

2. <u>Conduct pathway screening</u>: For sites with volatile chemicals in soil or groundwater, most regulatory guidance provides conservative screening criteria for preliminary evaluation of the VI pathway. Screening criteria used to evaluate the likelihood of VOC migration away from a source area at concentrations that would cause a VI impact are typically provided for groundwater and soil gas and less commonly for soil. Although exceedances of these criteria do not indicate that a VI impact has occurred or will occur, additional investigation of VI is often required if the maximum VOC concentration is greater than the screening value within a defined distance (typically 100 ft) of a VI receptor (i.e., a current or future building). For some common chemicals of concern (COCs), the USEPA screening criteria for groundwater are equal to drinking water standards. In addition, some soil gas screening criteria are less than or equal to analytical detection limits. As a result, few corrective action sites are screened out of further evaluation using these criteria.

3. <u>Complete building-specific evaluation</u>: For sites with volatile chemicals present at concentrations above the screening criteria, most guidance documents require a field investigation to determine the presence or absence of VI impacts to nearby buildings. When conducting a site-specific field investigation, USEPA guidance recommends collection of below-foundation (i.e., sub-slab) soil gas samples and indoor air samples. The USEPA guidance raises a number of data quality issues to be addressed as part of the field investigation, including indoor (background) sources of VOCs, spatial variability, temporal variability, and sample collection

and analytical variability. However, the guidance document does not provide a clear recommendation on the amount of data needed to account for these sources of variability and to make a definitive determination of the presence or absence of a VI impact. In the absence of clear guidance on the scope of the field investigation, the investigation approaches adopted by individual investigators have varied widely. As a result, disagreements may arise between parties involved at a site regarding the adequacy of a field investigation at a specific building.

Most state VI guidance documents utilize a step-wise investigation approach similar to the USEPA guidance. Also, most guidance documents utilize very low screening criteria for the preliminary evaluation. Some states (e.g., New York) do not allow screening based on subsurface VOC concentrations but instead require indoor air testing at all field investigation sites (New York Department of Health [NYDOH], 2006). In addition, the USEPA has indicated that revised VI guidance due in 2012 is unlikely to allow screening of the VI pathway based solely on soil gas concentration results (USEPA, 2010). Consequently, requirements for field investigation of the VI pathway will likely increase for sites with subsurface VOC impacts.

2.2 OBJECTIVES OF THE DEMONSTRATION

The overall objective of this project was to develop simple procedures utilizing easily obtained site-specific information to support a realistic pathway assessment involving significantly less effort than is currently required. For Tier 2-level evaluation and screening, soil texture and moisture content were evaluated as factors affecting VOC attenuation from groundwater into deep soil gas. For Tier 3, the utility of building pressure control was examined as a method to provide improved understanding of the impact of VI and indoor sources of VOCs on indoor air quality.

2.3 REGULATORY DRIVERS

To address concerns with VI, USEPA and state regulatory agencies have issued guidance on evaluating this pathway, providing conservative screening criteria for various VOCs. The high level of conservatism in the guidance reflects the current limitations of our understanding of the physical and chemical processes that contribute to the attenuation of vapors along the VI pathway. Development of validated Tier 2 VI screening procedures will serve to reduce the number of sites where detailed field investigations are required to evaluate the VI pathway. Development of a validated Tier 3 VI investigation procedure will improve the efficiency of the site-specific field investigation, when required.

3.0 TECHNOLOGY

This technology demonstration project has developed and validated 1) a Tier 2 VI screening procedure based on easily measured site-specific characteristics and 2) a streamlined Tier 3 evaluation procedure to determine the presence or absence of a VI impact to a specific building. The screening procedures can be used individually or together to provide maximum flexibility for cost-effective evaluation of VI at each site.

3.1 TECHNOLOGY DESCRIPTION

Tier 2 Screening Procedures: The groundwater-soil gas interface is a key target for site-specific evaluation because 1) transport across this interface varies significantly (>100x) between sites making the Tier 1 default overly conservative for a large proportion of sites evaluated and 2) easily obtained site-specific data can be used to support a protective but less conservative evaluation. At the groundwater-soil gas interface, a high moisture content, fine-grained soil layer serves as a significant barrier to the vertical migration of VOCs towards buildings. As a result, VOC attenuation along the VI pathway at sites with these soil layers can be much higher than at sites where these barriers to vertical diffusion are absent.

For this demonstration, we measured VOC attenuation from shallow groundwater through the soil column at seven sites exhibiting a variety of soil-type characteristics. Sample collection and analysis was conducted in a consistent manner across the sites, providing a comparable dataset for accurate assessment of the differences in VOC attenuation between these sites. The results of this demonstration document the higher VOC attenuation that occurs at sites with fine-grained soils within 2 ft above the water table. This, in turn, validates the use of higher Tier 2 screening criteria at sites with these documented soil conditions.

Streamlined Tier 3 Evaluation Procedure: When using indoor air sampling to evaluate VI, an investigator must address two confounding issues: 1) indoor sources of VOCs and 2) temporal variability in VI. The Tier 3 evaluation procedure addresses both of these issues using a streamlined investigation program that can be completed during a single 3-day sampling event. This streamlined investigation protocol uses induced negative building pressure to ensure that VI is “on” during one day of sampling and induced positive building pressure to ensure that VI is “off” during the following day’s sampling (see Figure 1). Samples collected during each pressure period are used to identify the primary sources of detected VOCs.

Controlled <u>negative</u> building pressure: VI is "on"

Controlled <u>positive</u> building pressure: VI is "off"

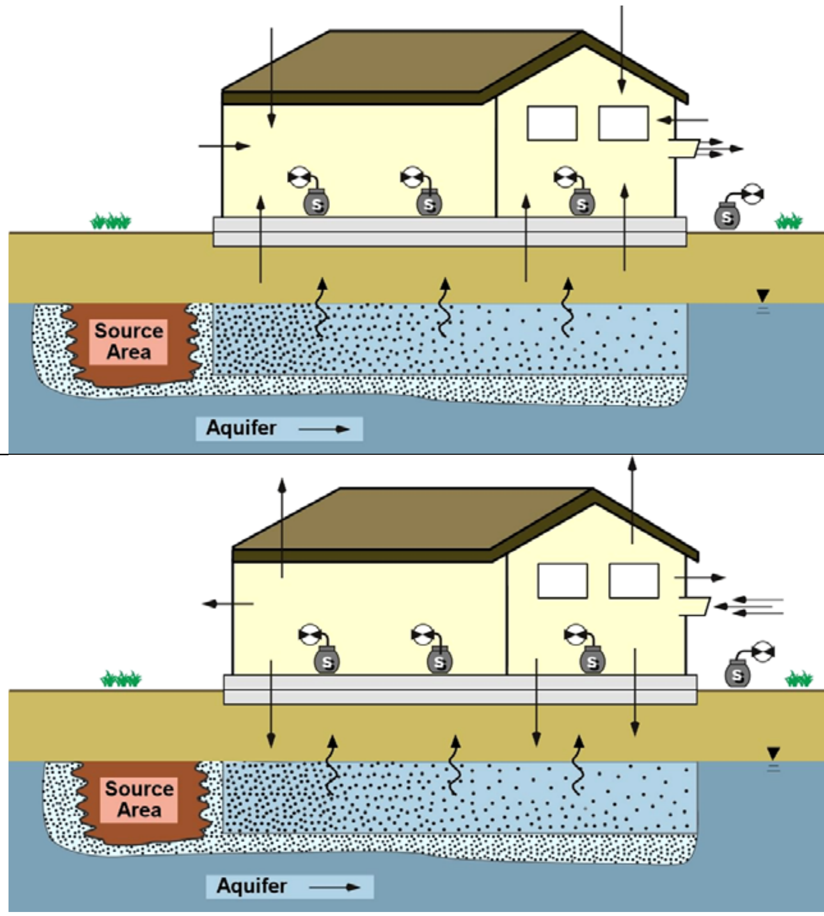

Figure 1. Conceptual illustration of building pressure control for the building-specific evaluation of VI.

For this project, the pressure control investigation procedure was demonstrated in six buildings. The results indicate that small (approximately 1Pascal [Pa]) pressure gradients are sufficient to control the flow of soil gas through a building's foundation. This was evaluated through indoor air measurements of radon, a naturally-occurring tracer for soil gas. VOC concentrations measured in indoor air under these controlled building pressure conditions were used to identify the primary source of the VOCs and to evaluate the building's susceptibility to VI. The results validate the use of the streamlined Tier 3 investigation procedure for the evaluation of VI at sites where a building-specific investigation is required.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The use of a tiered approach for the evaluation of corrective action sites has provided a cost-effective framework for focusing detailed site evaluations on exposure pathways that represent the greatest potential risk or remediation cost. Tier 1 uses generic screening criteria to eliminate the lowest risk pathways; Tier 2 uses limited site-specific information to support the use of less conservative screening criteria, where appropriate; and Tier 3 allows for detailed site investigations to accurately assess risk when warranted. States that have adopted this tiered

evaluation process within the context of risk-based corrective action have realized significant cost savings for their corrective action programs (Connor and McHugh, 2002).

As described above, USEPA and many states' VI guidance documents contain conservative (Tier 1) screening values and also provide some guidance for conducting detailed (Tier 3) field investigations of VI. However, there is a significant gap in the current VI evaluation process due to the absence of meaningful Tier 2 screening criteria that can be adjusted to reflect easily measured site characteristics that limit the migration of VOCs along the VI pathway.

Advantages:

Validation of Tier 2 screening procedures based on key site characteristics would allow a reduction in the level of conservatism in site screening without compromising protectiveness.

Validation of Tier 3 building-specific investigation procedures will better define the scope of field investigations, leading to more focused and efficient data collection efforts.

Limitations:

The Tier 2 screening procedures will be useful only at sites that meet the criteria for application (i.e., sites with high moisture content fine-grained soil layers within 2 ft above the water table). The Tier 2 screening procedure should not be applied to sites where the depth to groundwater is less than 5 ft bgs.

The streamlined Tier 3 evaluation procedure is targeted towards characterizing and controlling the building-specific factors that contribute to variability in VOC attenuation and associated VI impacts. The method is not applicable to very large or very leaky buildings where the building pressure cannot be easily controlled. In addition, the pressure control method does not eliminate the spatial variability of VOC concentrations that is observed at many investigation sites.

The Tier 3 evaluation procedure involves controlled depressurization of the building in order to induce conditions favorable for VI. When the results do show that VI occurs under depressurized conditions, these results will not be directly applicable to normal building operating conditions.

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4.0 PERFORMANCE OBJECTIVES

The primary objective of this demonstration study was to develop simple procedures for 1) Tier 2-level site-specific screening based on soil characteristics, and 2) limited building-focused Tier 3 field investigation of the VI pathway. This objective was met by:

- Collecting an extensive amount of data related to the specific site conditions that influence VOC attenuation at the test sites
- Collecting data in a consistent and comparable manner from sites with a broad range of site conditions (i.e., soil characteristics and building characteristics)
- Analyzing this data to obtain a thorough understanding of how site-specific conditions influence VI processes
- Documenting the impact of soil characteristics on VOC attenuation from groundwater (Tier 2 evaluation) and documenting the utility of measurement and control of building pressure for evaluation of VI impacts (streamlined Tier 3 evaluation).

Specific performance objectives and results are summarized in Table 1.

Table 1. Performance objectives and results.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Collection of data representative of site conditions	Soil type and moisture content; water elevation; VOC concentrations in groundwater, soil gas, and indoor air; building pressure gradients	Precision, accuracy, completeness, representativeness, and comparability as defined in Appendix D of the demonstration plan	Quantitative objectives for precision, accuracy, completeness, representativeness, and comparability were achieved with minor exceptions. The exceptions were typical of any significant environmental field program. The data quality for the demonstration program data set is acceptable and suitable for evaluation of the demonstration performance.
Validation of Tier 2 screening criteria and procedure (Hypothesis: VOC attenuation in the vadose zone is higher at sites with high moisture content, fine-grained soil layers on top of the shallowest water-bearing unit [i.e., a confining layer] or within the vadose zone.)	1) Measurement of vadose zone attenuation factors at each Tier 2 demonstration site 2) Identification of the presence or absence of a high moisture content, fine-grained soil layer at each site 3) Evaluation of the association between vadose zone attenuation of VOCs and the presence or absence of a high moisture content, fine-grained soil layer	A statistically significant difference in VOC attenuation between vadose zone attenuation of VOCs at sites with and without a high moisture content, fine-grained soil layer Statistical methods for data analysis are described in Section 5.6.2 of the demonstration plan.	A statistically significant difference was observed in VOC attenuation between the three sites with fine-grained soils within 2 ft above the water table and the four sites with coarse-grained soils within 2 ft above the water table ($p=0.01$). Moisture content was not useful for identification of high groundwater to deep soil gas attenuation sites. Field-measured soil (intrinsic) permeability was the best method for identification of fine-grained soil sites with high groundwater to deep soil gas attenuation. Visual determination of soil type provided an accurate classification (i.e., high attenuation vs. low attenuation) for six of the seven demonstration sites.

Table 1. Performance objectives and results (continued).

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Validation of Tier 3 investigation procedure (Hypothesis: manipulation of building pressure to create negative and positive building pressures 1) alters the distribution of VOCs in and around the building in a way that helps distinguish VI from background VOC sources and 2) allows measurement of pressure gradients to provide an improved understanding of foundation permeability.)	1) Measurement of VOC distribution in indoor air and sub-slab gas under negative and positive building pressure conditions 2) Measurement of pressure gradients across building foundation, across building envelope, and in shallow soils below building	Hypothesis Part 1: A statistically significant difference in VOC distribution between negative pressure conditions and positive pressure conditions Hypothesis Part 2: A statistically significant association between foundation permeability and sub-slab to indoor air attenuation factor	Hypothesis Part 1: Analysis of Variance (ANOVA) demonstrates a statistically significant difference in VOC distribution in indoor air between negative pressure conditions and positive pressure conditions ($p=0.03$). The change in VOC concentration in indoor air was different depending on the source of the VOC (i.e., above ground or subsurface). However, the predicted change in VOC concentration in sub-slab samples was not observed. Hypothesis Part 2: No statistically significant association between foundation permeability and sub-slab to indoor air attenuation factor was observed.
Qualitative Performance Objectives			
Development of Tier 2 screening criteria and procedure	Field-tested investigation procedures	Procedures for implementation of Tier 2 screening (see Section 5.6.4 of the demonstration plan)	Validated procedures for implementation of the Tier 2 screening procedure are described in Section 7.4 of this report.
Development of Tier 3 investigation procedure	Field-tested investigation procedures	Procedures for implementation of streamlined Tier 3 investigation (see Section 5.6.5 of the demonstration plan)	Validated procedures for implementation of the streamlined Tier 3 investigation procedure are described in Section 7.5 of this report.

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5.0 SITE DESCRIPTION

5.1 SITE LOCATION

This demonstration involved field validation of a Tier 2 screening procedure and a streamlined Tier 3 evaluation procedure at sites across the United States. Table 2 summarizes the demonstration sites. Each of these sites has a dissolved chlorinated solvent plume in shallow groundwater that has migrated away from the source area. Prior to the demonstration, each site had been investigated in sufficient detail to provide an understanding of the site geology and contaminant distribution and to allow identification of appropriate investigation locations.

Table 2. Demonstration sites.

Site Name	Site Location	Type of Demonstration
Former Pioneer Dry Cleaner	Houston, TX	Tier 2
Travis Air Force Base (AFB)	Fairfield, CA	Tier 2 and Tier 3
Naval Air Station, Jacksonville	Jacksonville, FL	Tier 3
Parris Island Marine Base	Parris Island, SC	Tier 2* and Tier 3
Tinker AFB	Oklahoma City, OK	Tier 2 and Tier 3
Hill AFB	Layton, UT	Tier 2 and Tier 3
Moffett Field Naval Air Station (NAS)	Moffett Field, CA	Tier 3
Space and Naval Warfare Systems Command (SPAWAR) Old Town Campus (OTC) Facility	San Diego, CA	Tier 2
NIKE Battery Site PR-58	N. Kingstown, RI	Tier 2
Industrial Site	Southeast TX	Tier 2

Note: * = Tier 2 demonstration not completed due to the presence of groundwater at a depth of less than 5 ft bgs.

5.2 SITE GEOLOGY/HYDROGEOLOGY AND CONTAMINANT DISTRIBUTION

A variety of sites and site conditions were evaluated in the Tier 2 and 3 demonstrations, as summarized in Table 3.

Table 3. Key site characteristics.

Site Name	Geology/Hydrogeology	Contaminant Distribution
Former Pioneer Dry Cleaner (Tier 2)	Depth to groundwater: 15–28 ft bgs For Tier 2: Confined aquifer; moist, fine-grained soil site	Tetrachloroethene (PCE) and degradation products in shallow groundwater at distances of up to 350 ft downgradient of facility.
Travis AFB (Tier 2 and Tier 3)	Depth to groundwater: 10–15 ft bgs For Tier 2: Unconfined or semi-confined; wet, fine-grained soil site	Trichloroethene (TCE) found in groundwater and shallow soil gas
NAS, Jacksonville (Tier 3)	Water table within a few ft of ground surface	PCE, TCE, and related degradation products found in site soil and groundwater; PCE detected in 1994 soil gas investigation
Parris Island Marine Base (Tier 2* and Tier 3)	Water table within a few ft of ground surface For Tier 2: site was intended to represent sites with coarse-grained soil in the vadose zone; however, Tier 2 demonstration could not be completed because of shallowness of the water table.	PCE in groundwater originated from a former dry cleaning facility; nearby sewer line release acted as secondary source.

Table 3. Key site characteristics (continued).

Site Name	Geology/Hydrogeology	Contaminant Distribution
Tinker AFB (Tier 2 and Tier 3)	Depth to groundwater: 10–15 ft bgs For Tier 2: Unconfined aquifer; wet, fine-grained soil site	TCE plumes in shallow groundwater. The Tier 2 demonstration focused on a plume extending east from Building 201. The Tier 3 demonstration was conducted in the mechanical room of Building 200; prior investigations found PCE in soil gas, shallow soils, and groundwater.
Hill AFB (Tier 2 and Tier 3)	Depth to groundwater: 7–12 ft bgs For Tier 2: Unconfined aquifer; fine to medium-grained soil site	TCE was the primary COC for both the Tier 2 and Tier 3 demonstrations.
Moffett Field NAS (Tier 3)	Depth to groundwater: 10–15 ft bgs	The primary COCs in the groundwater plume near the study area were TCE and PCE.
SPAWAR OTC Facility (Tier 2)	Depth to groundwater: 10–12 ft bgs For Tier 2: Unconfined aquifer; moist, fine-grained soil site	The primary COCs in groundwater, soil, and soil gas include PCE, TCE, cis-1,2-dicholoroethene (DCE), trans-1,2-DCE, and/or vinyl chloride (VC).
NIKE Battery Site PR-58 (Tier 2)	Depth to groundwater: 10–11 ft bgs For Tier 2: Unconfined aquifer; medium-grained soil site	The primary COCs in the groundwater include 1,1,2,2-tetrachloroethane (PCA), PCE, TCE, 1,1,2-trichloroethane (1,1,2-TCA), cis-1,2-DCE, trans-1,2-DCE, 1,1-dichloroethene (1,1-DCE), and VC.
Industrial Site (Tier 2)	Depth to groundwater: 13–18 ft bgs For Tier 2: Unconfined aquifer; wet, fine to medium-grained soil site	The primary COCs in the groundwater include PCE, TCE, 1,1,1-trichloroethane (1,1,1-TCA), 1,1,2-TCA, cis-1,2-DCE, 1,1-dichloroethane (1,1-DCA), 1,1-DCE, and VC.

Note: * = Tier 2 demonstration not completed due to the presence of groundwater at a depth of less than 5 ft bgs.

6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The purpose of this field demonstration was to validate 1) the use of confining layers and high moisture content fine-grained soil in the vadose zone as site-specific criteria for Tier 2 screening of the VI pathway and 2) the use of building pressure control for a streamlined Tier 3 evaluation of VI. Validation of the Tier 2 screening procedures and criteria required measurement of VOC attenuation at a number of sites with and without the defining characteristics to demonstrate a difference in VOC attenuation between these types of sites. Validation of the streamlined Tier 3 evaluation methods required application of the method at a number of buildings with different size, design, and foundation characteristics to demonstrate that the investigation methods consistently provide a clear determination of VI conditions.

6.1.1 Tier 2 Screening Criteria Based on Soil Conditions

The literature review and survey performed as part of this study identified the importance of high moisture content fine-grained soils as a barrier to VOC migration from groundwater to indoor air (GSI, 2008b). This suggested that VOC migration from a confined aquifer to vadose-zone soils will be limited and that high moisture content, fine-grained soil layers within the vadose zone would also limit the vertical migration of VOCs through the vadose zone. Field validation was conducted to verify whether consistently greater VOC attenuation was observable at sites with these characteristics.

As illustrated in Figure 2, the impact of an aquifer confining layer or fine-grained soil layer on VOC attenuation was tested through the measurement of aquifer confining conditions, soil parameters, and VOC concentrations at seven demonstration sites. The demonstration sites represented a range of confined and unconfined aquifer conditions in order to clearly document the differences in VOC attenuation between sites. The sampling program for the validation of the Tier 2 screening procedure is summarized in Table 4.

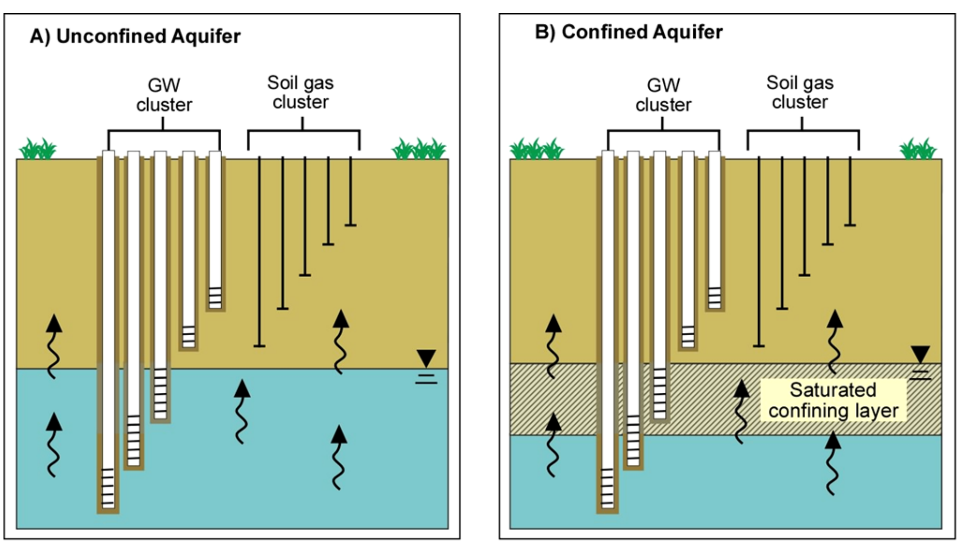

Figure 2. Conceptual plan for field validation of soil type and moisture content as basis for selection of Tier 2 VI screening criteria.

Table 4. Summary of Tier 2 evaluation sampling program.

Component	Matrix	Number of Samples	Analyte	Location
Validation of Tier 2 screening procedures and criteria: sample program for each demonstration site	Soil	2–4	Soil permeability (Field test)	Each groundwater sample point without water from each of 3 clusters
	Soil	12	Physical properties	4 soil intervals from each of 3 clusters
	Groundwater	9	VOCs	Each sample point with groundwater (3 clusters)
	Leak tracer (for each soil gas point)	15	Sulfur hexafluoride (SF_6)	Each soil gas sample point (3 clusters)
	Soil gas	15	VOCs	Each soil gas sample point (3 clusters)

6.1.2 Streamlined Tier 3 Evaluation Based on Building Pressure Control

For Tier 3 field evaluations of individual buildings, the field program included validation of a streamlined sampling program to evaluate the potential for VI under a range of building pressure conditions in a single sampling event. The Tier 3 procedure involved the following steps:

- Building Pressure Control: Measure VOC and radon concentrations at below-foundation sample points and in indoor air during an induced building depressurization event to evaluate VOC attenuation under "worst case" conditions and during an induced positive pressure event to evaluate conditions with VI "turned off" (Figure 3).
- VI Determination: Based on the difference in VOC concentrations between the negative and positive pressure sampling events, the potential for current and future VI impacts to a building is determined in a single round of sampling.

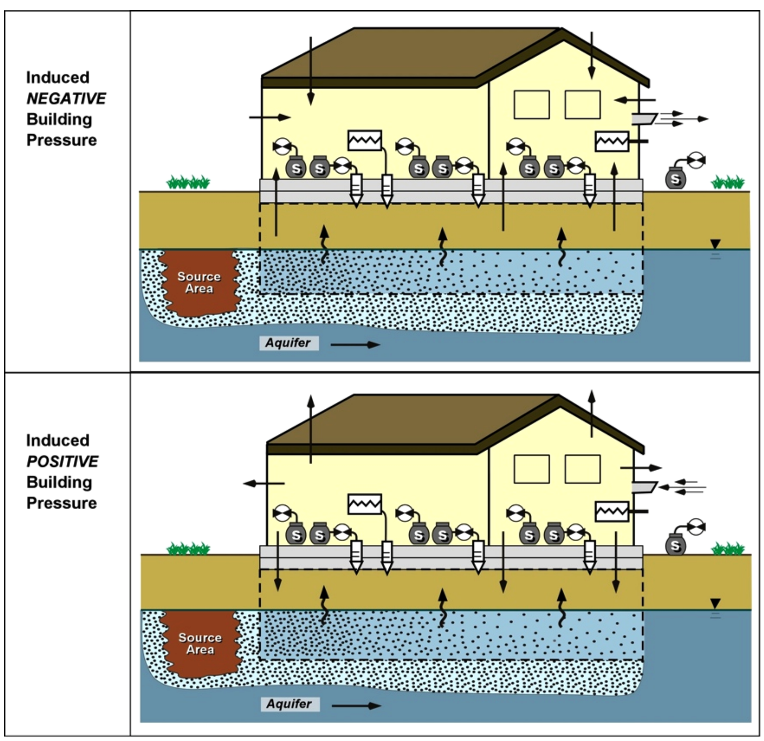

Figure 3. Conceptual basis for Tier 3 building pressure control evaluation of VI.

The sampling program for the validation of the streamlined Tier 3 evaluation procedure is summarized in Table 5.

Table 5. Summary of Tier 3 evaluation sampling program.

Component	Matrix	Number of Samples	Analyte	Location
Tier 3 building investigation (each test building)	Indoor air	6	Radon, SF_6, VOCs	Indoors, 3 locations (negative pressure and positive pressure events)
	Sub-slab vapor	6	Radon, SF_6, VOCs	Sub-slab, 3 locations (negative pressure and positive pressure events)
	Ambient air	1	Radon, SF_6, VOCs	Outdoors, upgradient, once at each location
	Pressure Gradient	NA	Differential pressure between indoor/outdoor and indoor/sub-slab space	Continuous sampling at various sample points during positive and negative pressure conditions

Note: Additional samples collected for some demonstrations.

6.2 BASELINE CHARACTERIZATION

As discussed in Section 5, each of the field demonstration sites had been characterized through prior site investigations. These investigations provided an understanding of the shallow geology and the distribution of site contaminants that was sufficient to support the design and implementation of the demonstration program at each site. As a result, no additional baseline characterization activities were conducted prior to the field demonstration at each site.

6.3 TREATABILITY OR LABORATORY STUDY RESULTS

No treatability or laboratory confirmation studies were conducted for this demonstration.

6.4 FIELD TESTING

6.4.1 Field Testing for Evaluation of Tier 2 Screening Procedure

At each site, the Tier 2 field testing program took place over the course of 5 days. The program consisted of soil gas and groundwater sample point installation in three clusters spaced across the site, collection of soils for geotechnical analysis, groundwater and soil gas sample collection, and soil permeability testing from the soil gas sampling points (see Figure 4).

Figure 4. Soil permeability measurement.

6.4.2 Field Testing of Tier 3 Evaluation Procedure

For validation of the Tier 3 procedure, the field testing program took place over the course of 3 days and consisted of the measurement of cross-foundation and building envelope pressure gradients (see Figure 5) and chemical concentrations under different building pressure conditions.

Figure 5. Pressure transducer installation for cross-foundation measurements.

6.5 SAMPLING METHODS

The sampling programs for the Tier 2 and 3 demonstrations are summarized in Tables 4 and 5. Analytical methods for applicable media sampled under either tier are summarized in Table 6.

Table 6. Analytical methods used for sample analysis.

Matrix	Analyte	Method	Container	Preservative	Holding Time
Soil (Tier 2)	Intrinsic Permeability/Native Hydraulic Conductivity (Lab measurement)	American Petroleum Institute (API) RP 40/ American Society for Testing and Materials (ASTM) D2434	Undisturbed core	None	None
	Porosity, total and air-filled	API RP 40	Undisturbed core	None	None
	Dry bulk density	API RP 40/ASTM D4564/ASTM D2937	Undisturbed core	None	None
	Volumetric moisture content	ASTM DD216/ASTM D4959/ASTM D4643	Undisturbed core	None	None
	Fraction organic carbon	Walkley-Black, USEPA 9060	Undisturbed core	None	None
Groundwater (Tier 2)	VOCs	USEPA 8260B	40 mL VOA vial	HCl	14 days
Vapor (Tier 2 and Tier 3)	Radon	McHugh et al., 2008	500 mL Tedlar bag	None	14 days*
	Chlorinated VOCs	USEPA TO-15	500 mL Tedlar bag or 1L Summa can	None	28 days
	SF_6	National Institute for Occupational Safety and Health (NIOSH) 6602	500 ml Tedlar bag or 1L Summa can	None	28 days

* = No holding time specified, but lab tests demonstrate accurate results after 14 days storage in Tedlar bag (McHugh et al., 2008).

6.6 SAMPLING RESULTS

Comprehensive sampling results for each Tier 2 and Tier 3 demonstration site are provided in the ER-200707 final report (GSI, 2012). The results are summarized below.

6.6.1 Validation of Tier 2 Screening Criteria and Procedures

The Tier 2 demonstration was completed at seven sites. For each site, the results were used to determine vadose zone soil characteristics and groundwater to deep soil gas attenuation factors (see Table 7).

Table 7. Relationship between vadose zone soil characteristics and groundwater to deep soil gas attenuation factors: site-based evaluation.

Site	Moisture Content (-)[2]	Predominate Soil Type at Water Table[6]	Native Hydraulic Conductivity (cm/sec)[1]	Field Soil Permeability (cm^2)[3]	Attenuation Factor (GW to Deep SG)[4]
Fmr. Pioneer Cleaners	0.90 +/- 0.063	Clay (CH/CL)	1.5H10^{-8}	1.5H10^{-10}	<8.5H10^{-6}
Travis AFB	0.83 +/- 0.094	Silty clay and clayey sand (CL/SC)	1.5H10^{-8}	1.1H10^{-8}	1.0H10^{-2}(1.0H10^{-3}-2.9H10^{-2})
Tinker AFB	0.96 +/- 0.043	Clayey silt (ML)	5.7H10^{-9}	4.7H10^{-11}	3.3H10^{-4}(<2.5H10^{-5}- 2.2H10^{-2})
SPAWAR OTC	0.77 +/- 0.18	Clayey silt (ML)	NM[5]	5.6H10^{-10}	1.5H10^{-5} (1.4H10^{-5}-1.5H10^{-5})
NIKE Battery PR-58	0.67 +/- 0.28	Sand (SW)	6.3H10^{-4}	1.4H10^{-8}	3.3H10^{-3}(2.8H10^{-4}-2.1H10^{-2})
Hill AFB	0.79 +/- 0.26	Sand and silty sand (SP/SM)	1.2H10^{-5}	1.7H10^{-8}	2.8H10^{-2}(1.7H10^{-2}-5.2H10^{-2})
SE Texas Industrial Site	0.72 +/- 0.21	Silty sand (SM)	7.6H10^{-6}	1.0H10^{-8}	0.15 (0.026 - 0.61)

(1) Geometric mean of 7 to 13 individual laboratory measurements
(2) Mean +/- standard deviation for 7 to 13 individual measurements
(3) Soil (intrinsic) permeability value based on geometric mean of 3 to 6 individual field measurements
(4) Geometric mean (range) of 5 to 6 individual groundwater to deep soil gas attenuation factors except for Former Pioneer Cleaners site. At Former Pioneer Cleaners site, attenuation factor calculated based on maximum VOC concentration in groundwater and VOC detection limit in soil gas because no VOCs were detected in any soil gas samples.
(5) NM = No measurement; All samples were fractured upon delivery to the laboratory or were too noncohesive, preventing the laboratory from analyzing for intrinsic permeability or native hydraulic conductivity.
(6) Soil type at or within 2 ft above the water table

6.6.2 Validation of Streamlined Tier 3 Evaluation Procedures

The Tier 3 demonstration was completed eight times in a total of six buildings. In the first four buildings (Building 828/Travis AFB, Building 103/Jacksonville NAS, New Dry Cleaner Facility/Parris Island, Building 102/Tinker AFB), the test sequence with controlled negative and positive pressure was completed once. In accordance with the Demonstration Plan Addendum, in the last two buildings (Arizona State University [ASU] Research House/Hill AFB and Building 107/Moffett Field), the test sequence included baseline, controlled negative, and controlled

positive pressure. This test sequence was completed twice to evaluate the reproducibility of the method.

At each building, the demonstration results were used to determine sub-slab attenuation factors for each pressure condition and to classify the magnitude of VI. The classifications of the magnitude of VI were based on the range of VOC and radon attenuation factors observed during the negative pressure cycle of each demonstration (i.e., conditions supporting flow of soil gas into the building), and show magnitude of VI in the buildings relative to each other. The building-specific VI classifications are summarized in Table 8.

Table 8. Attenuation factors measured for chemicals with subsurface sources.

Chemical	Attenuation Factor		Magnitude of VI*
	Negative Pressure	Positive Pressure	
Building 828, Travis AFB			
TCE	0.097"0.12	NA	Low
Radon	3.0H10^{-4}"4.1H10^{-5}	NA	
Building 103, Jacksonville NAS			
PCE	7.7H10^{-5}"3.8H10^{-5}	3.1H10^{-5}"1.6H10^{-5}	Medium (High)
TCE	8.4H10^{-5}"4.0H10^{-5}	7.1H10^{-5}"2.9H10^{-5}	
Radon	9.3H10^{-4}"6.2H10^{-4}	1.0H10^{-19}"2.9H10^{-20}	
Parris Island New Dry Cleaner Facility			
PCE	0.15"0.094	0.43"0.20	Low
Radon	6.0H10^{-5}"1.2H10^{-5}	6.8H10^{-5}"2.3H10^{-5}	
Building 102, Tinker AFB			
PCE	NA	NA	Low
Radon	4.6H10^{-4}"4.6H10^{-4}	NA	
ASU Research House, Hill AFB (Round 1)			
1,1-DCE	0.036"0.042	NA	High
TCE	0.044"0.049	0.029"0.027	
Radon	8.6H10^{-3}"1.2H10^{-2}	NA	
ASU Research House, Hill AFB (Round 2)			
1,1-DCE	0.027"0.029	4.4H10^{-4}"6.3H10^{-4}	High
TCE	0.047"0.070	8.6H10^{-3}"3.4H10^{-3}	
Radon	8.4H10^{-3}"1.1H10^{-2}	1.3H10^{-4}"2.1H10^{-4}	
Building 107, Moffett Field (Round 1)			
TCE	1.1"0.81	0.025"0.019	Medium (High)
PCE	0.61"0.40	0.017"0.012	
Radon	1.2H10^{-3}"1.1H10^{-3}	5.3H10^{-5}"1.1H10^{-4}	
Building 107, Moffett Field (Round 2)			
TCE	4.6"3.4	1.1"1.2	Medium (High)
PCE	1.6"0.76	0.024"0.022	
Radon	9.9H10^{-4}"7.1H10^{-4}	NA	

NA = Not applicable, concentration in ambient air greater than concentration in indoor air.
* = Magnitude of VI based on the radon attenuation factor (AF) during the negative pressure condition. For the purposes of this data comparison: High = Radon AF>5H10^{-3}, Medium = Radon AF between 5H10^{-3} and 5H10^{-4}, Low = Radon AF<5H10^{-4}. For the "Medium" VI sites, the secondary classification is High = Radon AF>5H10^{-4}.

7.0 PERFORMANCE ASSESSMENT

7.1 COLLECTION OF DATA REPRESENTATIVE OF SITE CONDITIONS

The collection of site data that is representative of actual site conditions was achieved by adhering to the specified sampling and analysis procedures and the Quality Assurance Project Plan (QAPP). The data quality review included sampling and custody procedures, holding time, sample conditions upon receipt at the laboratory, field duplicates, laboratory duplicate and blank analyses, and a completeness assessment. The minor data quality exceptions noted were typical of environmental field programs. None of the exceptions limit the usability of the results obtained.

<u>Finding</u>: The data quality for the demonstration program data set is acceptable and suitable for evaluation of the demonstration performance.

7.2 VALIDATION OF TIER 2 SCREENING CRITERIA AND PROCEDURES

The hypothesis for validation was that VOC attenuation in the vadose zone is higher at sites with high moisture content, fine-grained soil layers on top of the shallowest water-bearing unit (i.e., a confining layer) or within the vadose zone. At each demonstration site, good consistency was observed in groundwater to deep soil gas attenuation both between individual VOCs and between soil gas clusters, thus supporting the hypothesis that specific site characteristics can be used to predict VOC attenuation within the subsurface. The variation between attenuation factors for a single site ranged from 1.1H to 150H. This range was much smaller than the 18,000H range of geometric mean attenuation factors between sites.

In order to identify the relationship between measured site characteristics and VOC attenuation, a comparison of these characteristics and groundwater to deep soil gas attenuation factors was completed both qualitatively and quantitatively. Key evaluations included:

<u>Moisture Content</u>: A qualitative and quantitative evaluation (i.e., regression analysis) suggested that moisture content is not a good predictor of groundwater to deep soil gas attenuation.

<u>Soil Type (Visual Determination)</u>: The sites with silt and clay soils within 2 ft above the water table (Pioneer Cleaners, Tinker AFB, and SPAWAR OTC) generally had lower attenuation factors (i.e., exhibited higher attenuation) compared to sites with sandy soils (NIKE PR-58, Hill AFB, and the Industrial Site). Travis AFB appeared to be anomalous with finer-grained soils within 2 ft of the water table but VOC attenuation more consistent with the coarser-grained soil sites.

<u>Native Hydraulic Conductivity (Lab Measurement)</u>: There was generally good correlation between native hydraulic conductivity and VOC attenuation. However, regression analysis indicated that laboratory-measured native hydraulic conductivity is not a good method to identify fine-grained soil sites with high groundwater to deep soil gas attenuation.

<u>Soil Permeability (Field Measurement)</u>: There was good correlation between soil permeability and VOC attenuation. Regression analysis of log soil permeability versus log attenuation factor

measured at the individual cluster locations showed a statistically significant relationship ($p=0.004$); the same analysis on a site-by-site basis also showed statistical significance ($p=0.04$). A two sided t-test indicated a statistically significant difference in attenuation factors between the three sites with lower soil permeability and the four sites with higher soil permeability ($p=0.01$). This analysis indicates that field-measured soil permeability is a good method to identify fine-grained soil sites with high groundwater to deep soil gas attenuation. The geometric mean groundwater to deep soil gas attenuation factor at the three sites with lower soil permeability was 3.5×10^{-5}. The geometric mean attenuation factor at the four sites with higher soil permeability was 1.9×10^{-2}, a 500-fold difference between the two types of sites.

Finding: Visual determination of soil type and field measurement of soil permeability appeared to lead to the most reliable correlations between site characteristics and VOC attenuation.

The demonstration at seven sites has resulted in validation of the Tier 2 Screening Procedure:

- Although moisture content was not a useful predictor of VOC attenuation, soil type was found to be a useful predictor. Significantly higher VOC attenuation was observed at sites with fine-grained soils within 2 ft above the water table compared to coarse-grained soils in this interval ($p=0.01$).
- Visual determination of soil type and laboratory-measured hydraulic conductivity provided accurate classification of sites as finer-grained or coarser-grained for six of seven sites. Field-measured soil permeability provided an accurate classification for all seven demonstration sites.
- A 500-fold difference in the geometric mean VOC attenuation factors was observed between the fine-grained soil sites and the coarse-grained soil sites, with higher attenuation at the fine-grained soil sites.

The specific procedures recommended for implementation of the Tier 2 Screening Procedure are provided in Section 7.4.

7.3 VALIDATION OF TIER 3 INVESTIGATION PROCEDURE

Full validation of the streamlined Tier 3 evaluation required two key elements: 1) observation of differences in VOC distribution between negative pressure and positive pressure conditions that support differentiation between VI and background sources of VOCs and 2) a correlation between cross-foundation pressure gradient measurements and the magnitude of observed VI.

For each demonstration building, each of the VOCs commonly detected in indoor and sub-slab samples was classified as originating primarily from subsurface sources or indoor sources based on 1) prior knowledge of VOCs present in subsurface sources and 2) the sub-slab to indoor attenuation factors measured under negative pressure conditions. For all of the demonstration sites, benzene and toluene were identified as originating from aboveground sources and detected chlorinated VOCs (PCE, TCE, and/or 1,1-DCE) were identified as originating from subsurface sources.

Based on this preliminary classification, the difference in measured concentrations between negative pressure conditions and positive pressure conditions has been evaluated. The predicted concentration changes are illustrated in Figure 6.

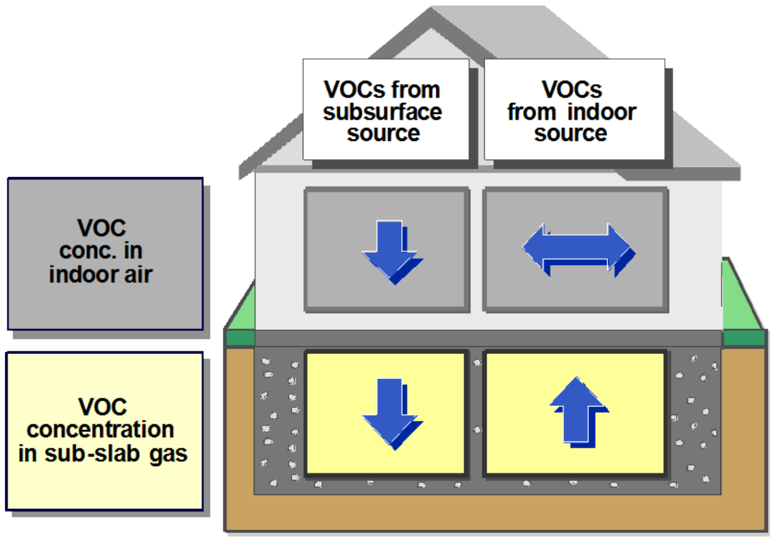

Figure 6. Predicted change in VOC concentration between negative building pressure and positive building pressure sampling events, under permeable foundation conditions.
(e.g., the indoor air concentrations of VOCs originating from a subsurface source are expected to be lower under positive building pressure conditions compared to negative building pressure conditions)

7.3.1 Utility of Building Pressure Control for Evaluation of VI

The pressure control method was applied at six different buildings. Pressure control was not achieved at the Parris Island New Dry Cleaning Facility because of ventilation slats built into the structure. For the other five buildings, pressure control was effective in turning VI on and off (Figure 3). The clearest evidence of this is provided by the measurement of radon concentrations during the different pressure conditions (Figure 7). At four of the five buildings with successful pressure control, radon concentrations in indoor air were higher than ambient (outdoor) concentrations during negative building pressure and decreased to ambient concentrations during positive building pressure. In the fifth building (at Tinker AFB), the indoor radon concentration was equal to ambient concentrations during both sampling events indicating an absence of VI under all conditions. For all five of these buildings, the response to pressure control for COCs with subsurface sources (i.e., the chlorinated VOCs) generally matched the response of radon.

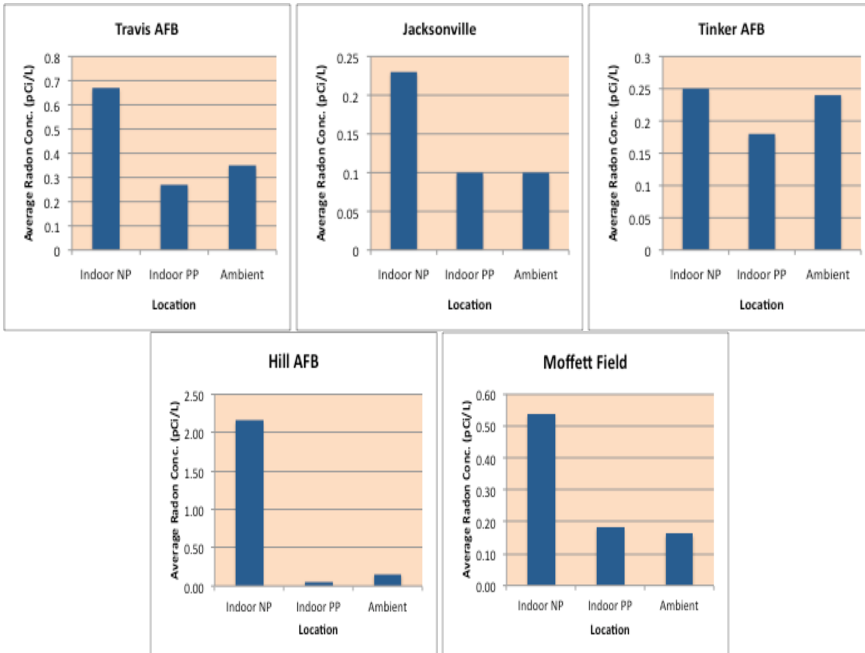

Figure 7. Effect of building pressure control on concentration of radon in indoor air.

7.3.2 Impact of Pressure Control on COC Concentrations

For chemicals with an aboveground source (i.e., benzene, toluene, and SF_6), the change in concentration in indoor air between negative and positive pressure conditions matched the prediction (i.e., no change) for 12 out of 20 cases. For four of the remaining eight cases, the increase or decrease in indoor air concentration was matched by a similar change in ambient air concentration indicating that the change was independent of the change in building pressure condition. For chemicals with a subsurface source (i.e., the chlorinated VOCs), the observed concentration trend in indoor air matched the prediction (i.e., decrease) in 17 of 19 cases.

For chemicals with an aboveground source, the change in concentration in the sub-slab matched the prediction (i.e., increase in concentration) in only five out of 20 cases. For chemicals with a subsurface source, the concentration change in the sub-slab matched the prediction (i.e., decrease) in only six of 19 cases. The prediction regarding the change in sub-slab concentration was based on the hypothesis that the conditions at sub-slab measurement points would be influenced by advective flow of air through cracks and penetrations in the foundation. The absence of the predicted response at many of the sub-slab sample points may be due to poor communication between these measurement points and slab cracks and penetrations that support advective flow.

<u>Finding</u>: The predicted changes in COC concentrations generally occurred in indoor air but did not typically occur below the building foundation.

7.3.3 Correlation between Cross-Foundation Pressure Gradients and VI

A second aspect of the Tier 3 testing program was to evaluate whether the magnitude of the cross-foundation pressure gradient induced by the building pressurization will provide an indication of the building foundation permeability and resulting potential for future VI impacts.

Finding: The demonstration dataset does not show a statistically significant correlation between foundation permeability (as determined by measurement of cross-foundation pressure gradients) and VI.

7.3.4 Other Analysis of Tier 3 Demonstration Results

In addition to the performance assessment envisioned in the Demonstration Plan, the Tier 3 demonstration dataset supports the following additional evaluations and observations.

7.3.4.1 Evaluation of Reproducibility

In order to evaluate the reproducibility of the Tier 3 investigation procedure, the Tier 3 demonstration was conducted twice in each of the two final demonstration buildings: ASU Research House, Hill AFB and Building 107, Moffett Field. As shown in Figure 8, the change in indoor air COC concentrations was generally similar over the two rounds of testing. Similar results were found in sub-slab concentrations. This demonstration of reproducibility serves to increase confidence that the Tier 3 investigation procedure provides reliable results.

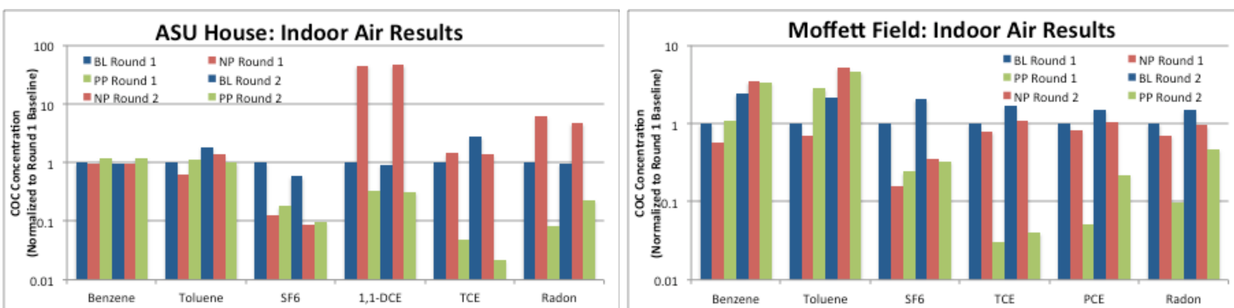

Figure 8. Comparison of indoor air concentration results over two rounds of testing.

7.3.4.2 Control of Temporal Variability in VI

For some buildings (e.g., ASU Research House, Hill AFB), VI is episodic. For such buildings, a single standard (i.e., conventional) VI testing event may not accurately identify a true VI problem. As a result, several standard testing events may be required to confirm an absence of VI.

The Tier 3 demonstration dataset indicates that building depressurization can be used to evaluate the potential for episodic VI during a single testing event. For the ASU Research House, the baseline sampling results showed an absence of VI. However, the sample results from the controlled negative pressure condition showed clear VI indicating a potential for VI to occur under some building operating conditions. The results from the ASU Research House show that

the controlled negative pressure condition serves to flag the building as high priority for additional investigation if the building is conducive to episodic VI. In contrast, an absence of VI under controlled negative pressure conditions would serve to provide a high level of confidence that there is little to no potential for episodic VI.

7.3.4.3 Limitations of Sub-Slab Samples for Evaluation of VI

The current standard building-specific VI sampling program uses indoor air and sub-slab sample results to evaluate the presence or absence of VI using a multiple lines of evidence data evaluation approach (Interstate Technology & Regulatory Council [ITRC], 2007). A key line of evidence is the detection of COCs in sub-slab samples at concentrations at least 10 times those detected in indoor air. Based on the dilution and attenuation that occurs between the subsurface and indoor air, VI is considered unlikely to result in COC concentrations in indoor air that are greater than 10% of the sub-slab concentrations. Higher than expected concentrations of COCs in indoor air is considered strong evidence that indoor or ambient sources are contributing to the concentrations in indoor air.

The Tier 3 demonstration dataset illustrates the limitations of this line of evidence for the evaluation of VI. At Building 107, Moffett Field, the sub-slab concentrations of TCE and PCE were similar to the indoor air concentration during all three test conditions (baseline, negative pressure, and positive pressure) while the radon concentrations were 500 to 1000 times higher than in indoor air. Using the standard lines of evidence approach, this would be considered strong evidence of an indoor source of TCE and PCE. However, the results from the controlled negative and positive pressure test conditions clearly showed that TCE, PCE, and radon all originated from subsurface sources (i.e., the concentrations of all three COCs were elevated in indoor air relative to outdoor air concentration during the negative pressure condition but equivalent to outdoor air concentrations under the positive pressure condition).

7.3.4.4 Time Required for Indoor Air Concentrations to Respond to Change in Pressure Condition

For the Tier 3 field demonstration program, each pressure condition was maintained for at least 12 hours prior to initiation of sample collection in order to allow the VOC concentrations in indoor air to respond to the change in building pressure. If the indoor air is well mixed (i.e., if the building behaves like a continuous-stir tank reactor), then three air exchanges should be sufficient to achieve VOC concentrations within approximately 10% of the new steady-state conditions. For the five buildings where air exchange rates were measured, the air exchange rates under the pressure control conditions ranged from 14 day^{-1} to 80 day^{-1}. For these buildings, three air exchanges would occur within 1 to 5 hours after initiation of the pressure control condition. As a result, 12 hours should have been more than sufficient to attain steady-state conditions even in the absence of complete mixing. This theoretical analysis assumes that VOC sinks in the subsurface or building do not cause a lag in the response time.

At the ASU Research House, supplemental indoor air analyses were conducted using the field portable HAPSITE gas chromatography (GC)/mass spectrometry (MS) at one of the indoor air sample locations at a frequency of every 1 to 2 hours for the duration of the demonstration. The results from these supplemental analyses allow a direct evaluation of the time required for VOC

concentrations in indoor air to respond to a change in the building pressure condition. Although both key COCs, TCE and 1,1-DCE, exhibit temporal variability over the course of the demonstration, the concentration changes induced by changes in building pressure appear to occur within 2 to 4 hours after the change in pressure. This response time is consistent with the theoretical analysis discussed above. For this building, the HAPSITE data supports the prediction that approximately three air exchanges are sufficient for VOC concentrations in indoor air to respond to a change in building pressure.

7.3.5 Summary of Validation of Tier 3 Investigation Procedure

The demonstration program has resulted in validation of the Tier 3 Investigation Procedure:

- Site-by-site evaluations (e.g., Section 7.3.1) demonstrate the utility of the Tier 3 procedure in controlling VI. Additionally, ANOVA conducted on the entire Tier 3 demonstration dataset shows that the control of building pressure provides the ability to distinguish between COCs originating from subsurface sources versus COCs originating from aboveground sources based on the change in concentration in indoor air between the controlled negative pressure condition and the controlled positive pressure condition ($p=0.03$).
- The change in COC concentration in indoor air between the controlled negative pressure condition and the controlled positive pressure condition matched the predicted change for subsurface COCs (i.e., decrease in concentration) for 17 of 19 cases and matched the predicted change for aboveground COCs (i.e., no change or change matching the change in ambient concentrations) in 16 of 20 cases.

Some of the specific hypotheses were not validated:

- The changes in COC concentration in sub-slab samples did not generally match the prediction.
- There was no clear correlation between measured foundation permeability and the magnitude of VI in the six demonstration buildings.

The validation dataset supports some additional findings not discussed in the original demonstration plan:

- Implementation of the investigation procedure twice in each of two demonstration buildings showed that the procedure yields reproducible results.
- The Tier 3 Investigation Procedure can be used to control temporal variability in buildings with episodic VI (e.g., ASU Research House, Hill AFB).
- The Tier 3 Investigation Procedure can be used to accurately identify VI in buildings where the standard lines of evidence approach would incorrectly suggest an indoor source (e.g., Building 107, Moffett Field).

The specific procedures recommended for implementation of the Tier 3 Field Investigation Procedure are provided in Section 7.5.

7.4 TIER 2 SCREENING CRITERIA AND PROCEDURES

The goal of the field demonstration for the Tier 2 screening procedure was to produce a validated protocol to apply to other sites with VI concerns. This section addresses routine application of the Tier 2 screening procedure at VI investigation sites. The Tier 2 screening procedure involves 1) identification of sites with fine-grained soils within 2 ft above the water table and 2) application of an adjustment factor to the Tier 1 screening criteria to account for the higher VOC attenuation observed at these sites.

7.4.1 Identification of Sites with Fine-Grained Soils at the Water Table

The presence of fine-grained soil within 2 ft above the water table can be determined using one of two methods: 1) visual inspection of soil cores or 2) field measurement of soil permeability.

- Visual inspection of soil cores: Boring logs generated during the installation of groundwater monitoring wells or soil borings can be used to determine the presence of fine-grained soils within two ft above the water table. When using this method, a site should be classified as fine-grained if the soils within 2 ft above the water table are predominately silts or clays. This method provided an accurate classification of soil type at six of the seven demonstration sites.
- Soil permeability: Soil permeability can be measured in the field; calculation methods are described in Appendix C of the final report. When using this method, a site with a geometric mean soil permeability of less than 1H10^{-9} cm^{2} should be classified as a fine-grained soil site. This method proved accurate at all seven demonstration sites.

The choice between the simpler and less expensive but potentially less accurate classification method (i.e., visual inspection) versus the more complex but potentially more accurate classification method (i.e., field measurement) should be based on consideration of other uncertainty associated with the pathway evaluation. If VOC concentrations are only slightly above Tier 1 screening levels or if the visual classification is obvious based on identification of a thick clay confining layer within 2 ft above the water table, then field measurement of soil permeability is less necessary.

7.4.2 Application of Adjustment Factor to Tier 1 Groundwater Screening Criteria

Sites with fine-grained soils within 2 ft above the water table were found to exhibit an average of 500 times more attenuation of VOCs from groundwater to deep soil gas. Based on this observation, Tier 1 groundwater screening criteria for the VI pathway that have been established to be protective at all types of sites can be adjusted upward by 100 times based on the determination that a site has fine-grained soils within 2 ft above the water table. We recommend an adjustment of 100 times rather than 500 times as a conservative measure to account for potential variability in groundwater to deep soil gas attenuation not characterized during the demonstration. An example application is as follows:

> If the Tier 1 Groundwater Screening Concentration for PCE is 1 µg/L (e.g., New Jersey Department of Environmental Protection [NJDEP], 2007), then the Tier 2 screening value for a site with fine-grained soil within 2 ft above the water table would be 100 µg/L.

The adjustment factor is only intended to be applied to generic Tier 1 screening criteria that do not already include a consideration of soil type.

The resulting Tier 2 screening concentrations should be compared to VOC concentration measurements from conventional monitoring wells (i.e., ≥5 ft well screens) screened at the top of the shallowest water-bearing unit. The screening concentrations are not applicable for grab samples or samples collected directly from the top of the water-bearing zone using very short well screens. The VOC concentrations in these samples may be biased low due to the loss of VOCs to the vadose zone.

7.5 TIER 3 INVESTIGATION PROCEDURE

The goal of the field demonstration for the Tier 3 investigation procedure was to produce a validated procedure for a streamlined building investigation program that provides a reliable determination of the presence or absence of a VI concern for that building. For the validation, a large dataset was required to fully evaluate the procedure's performance. For routine application, the recommended investigation procedure is less extensive.

7.5.1 Overview of Tier 3 Investigation Procedure

Conceptually, sampling of indoor air is the most direct method to evaluate the presence or absence of VI at a specific building. However, sampling of indoor air during a single sampling event has two key limitations: 1) the sampling event might not be scheduled during "worst case" VI conditions when flow of soil gas into the building is maximized, and 2) VOCs detected in indoor air samples cannot easily be attributed to a specific source (i.e., VI or an indoor source). Currently, some state regulatory guidance documents recommend multiple indoor sampling events or building sampling only during specific weather conditions (i.e., during the heating seasons) in order to characterize "worst case" VI conditions. In addition, most regulatory guidance documents recommend use of "multiple lines of evidence" to distinguish between VI and indoor sources of VOCs.

For buildings with concrete foundations, the streamlined Tier 3 building sampling procedure uses the manipulation of building pressure to "turn on" and "turn off" VI. Indoor air samples collected under controlled negative building pressure conditions are used to characterize indoor air quality under conditions of maximum soil gas entry into the building while indoor air samples collected under controlled positive pressure building conditions are used to characterize indoor air quality in the absence of soil gas entry. As a result, VOCs detected in indoor air under positive building pressure conditions are generally representative of sources other than VI. During a single 3-day sampling event, this streamlined evaluation procedure documents indoor air quality under a range of building pressure conditions allowing the determination of the impact of VI and other VOC sources on indoor air quality.

7.5.2 Method Implementation

Sampling Program: The Tier 3 pressure control method requires measurement of indoor radon concentrations under baseline conditions and indoor and ambient radon and VOC concentrations under negative building pressure conditions and positive building pressure conditions over a 3-day period (see Table 9).

Table 9. Tier 3 pressure control method sampling program: routine application.

Pressure Condition	Matrix	Number of Samples	Analyte	Location
Baseline (Day 1)	Indoor air	1	Radon	Open area on lowest building level
Negative Pressure (Day 2)	Indoor air	1 -3	Radon, VOCs	Open area on lowest building level plus up to two additional samples based on building layout
	Ambient air	1	Radon, VOCs	Upwind location
Positive Pressure (Day 3)	Indoor air	1 -3	Radon, VOCs	Open area on lowest building level plus up to two additional samples based on building layout
	Ambient air	1	Radon, VOCs	Upwind location

Data Interpretation: The magnitude of VI in the building is evaluated by comparing the VOC concentration in indoor air measured under negative building pressure to the VOC concentration measured under positive building pressure conditions. The difference in VOC concentration between the two test conditions is the VOC concentration attributable to VI. For example, if the concentration of PCE in indoor air is 5 $\mu g/m^3$ under negative building pressure conditions and 1 $\mu g/m^3$ under positive building pressure conditions, then the PCE in indoor air under negative pressure conditions is primarily attributable to VI. Based on the variability typically observed between the indoor air measurement locations, the resulting dataset is usually not suitable for a quantitative determination of the impact of VI (i.e., for the PCE example, an estimate that 80% of the PCE in indoor is attributable to VI would have large uncertainty). However, the resulting dataset is usually sufficient for identification of the primary source of each COC in indoor air.

The radon results are used as a positive control tracer for the movement of soil gas into the building. When soil gas is entering the building through the building foundation, the concentration in indoor air will be higher than the concentration in ambient air. Thus, the radon results will be used to verify that soil gas entry into the building is occurring under negative pressure conditions and eliminated under positive pressure conditions. The interpretation of the radon results is illustrated in Table 10.

Table 10. Use of radon concentration data to verify method performance.

Comparison	Condition	Interpretation
Radon concentration in indoor air: baseline vs. negative pressure	Baseline concentration ≤ negative pressure condition	Negative pressure condition has maximized VI.
	Baseline concentration > negative pressure condition	Increased air exchange associated with building depressurization may have caused dilution of VI impact.
Radon concentration under positive pressure: indoor vs. ambient	Concentration in indoor air = concentration in ambient air	Positive pressure condition has "turned off" VI.
	Concentration in indoor air > concentration in ambient air	Some VI may be occurring under positive pressure conditions.

8.0 COST ASSESSMENT

8.1 COST MODEL

Both the Tier 2 screening and Tier 3 investigation procedures are fundamentally site characterization methods. As such, key cost components for the methods are 1) sample point installation, 2) sample collection and analysis, and 3) data analysis and reporting.

8.2 COST DRIVERS

The cost for implementation of the Tier 2 screening procedure and Tier 3 investigation procedure is not expected to vary significantly based on specific site characteristics. The Tier 2 screening procedure can typically be implemented utilizing existing site data without significant cost. The Tier 3 investigation procedure uses a fixed sampling program that will not vary based on site-specific characteristics.

8.3 COST ANALYSIS

The cost estimates for implementation of the Tier 2 and Tier 3 procedures assume implementation by experienced personnel. For any procedure or field program, the time required for the first implementation by inexperienced personnel would be significantly higher.

8.3.1 Operational Implementation Costs for Tier 2 Screening Procedure

The Tier 2 screening procedure involves 1) identification of sites with fine-grained soils within 2 ft above the water table and 2) application of an adjustment factor to Tier 1 screening criteria to account for higher VOC attenuation observed at such sites. Operational implementation costs are associated with the first step (determination of whether the site has fine-grained soils within 2 ft above the water table). As discussed above, two methods were validated at the demonstration sites. The presence of fine-grained soils within 2 ft above the water table can be determined either by 1) visual inspection of soil cores (or review of boring logs generated during the installation of borings or monitoring wells) or 2) field measurement of soil permeability. Estimated costs to implement these alternatives are summarized in Table 11.

Table 11. Costs for routine implementation of Tier 2 screening.

Cost Element	Labor Hours	Estimated Cost
Method 1: Visual Inspection of Cores or Logs		
1. Visual inspection of cores during implementation of other field program or collection and review of existing boring logs	2	$200
2. Documentation of soil type observed within 2 ft of the water table	1	$100
Total Estimated Implementation Costs for Method 1		**$300**
Method 2: Field Measurement of Soil Permeability		
1. Prepare for and conduct field test during implementation of other field program. Assumptions: 1) test conducted at 3 locations; 2) test points already installed as part of other field program; and 3) test is conducted in conjunction with other field work (i.e., no additional mobilization time required).	6	$600
2. Analysis of field measurement; documentation of field methods and calculation methods.	4	$400
Total Estimated Implementation Costs for Method 2		**$1000**

Note: Labor costs of $100/hour were assumed.

8.3.2 Operational Implementation Costs for Tier 3 Investigation

The Tier 3 investigation procedure described in Section 7.5 involves manipulating building pressure and collecting air samples during three different pressure conditions: baseline, negative pressure, and positive pressure. Estimated costs to implement the Tier 3 procedure are shown in Table 12. The sampling itself takes place over the course of 3 days, with 4 to 6 hours per day for each of two persons assumed for equipment checks, setup, and pickup.

Table 12. Costs for routine implementation of Tier 3 procedure.

Cost Element	Category				Unit Cost	Cost	Subtotal
1. Project planning and preparation[1]	Labor	Senior project scientist/Engineer	4	hours	$150/hr	$600	
	Labor	Project scientist/ Engineer	6	hours	$100/hr	$600	$1200
2. Pressure control and sampling field program	Labor	Senior project scientist/Engineer	16	hours	$150/hr	$2400	
	Labor	Project scientist/ Engineer	16	hours	$100/hr	$1600	
	Equipment rental	Floor fan, differential pressure recorder	$225	per building	-	$225	
	Sample analysis	VOCs (4 samples + 1 field duplicate)	5	samples	$270/spl	$1350	
	Sample analysis	Radon (5 samples + 1 field duplicate)	6	samples	$110/spl	$660	$6235
3. Data evaluation and reporting[1]	Labor	Senior project scientist/Engineer	4	hours	$150/hr	$600	
	Labor	Project scientist/ Engineer	6	hours	$100/hr	$600	$1200
Project Total:							**$8635**

Note: 1) Estimates for project planning (Task 1) and (Task 3) are the per building cost assuming application of the procedure at four or more buildings during a single field program. The per building costs would be larger if applied to only one to three buildings.
2) Cost estimates do not include travel to the site. The actual number of samples will depend on the building configuration.

9.0 IMPLEMENTATION ISSUES

The cost for implementation of the Tier 2 screening procedure and Tier 3 investigation procedure is not expected to vary significantly based on specific site characteristics. Rather, the cost benefit of implementing these procedures in lieu of the current standard VI pathway evaluation will depend primarily on local regulatory requirements.

9.1 IMPLEMENTATION ISSUES FOR TIER 2 SCREENING PROCEDURE

Applicability: The Tier 2 screening procedure will only be useful at certain sites (i.e., sites with fine-grained soil layers within 2 ft above the water table. Sites with exclusively sandy soils and sites in dry climates with low moisture content soils will not benefit). The Tier 2 screening procedure should not be applied to sites where the depth to groundwater is less than 5 ft bgs.

Regulatory Acceptance: A manuscript for peer-review publication is currently under development. Publication of findings in a peer-reviewed journal should enhance regulatory acceptance of the procedure.

9.2 IMPLEMENTATION ISSUES FOR TIER 3 INVESTIGATION PROCEDURE

Applicability: The Tier 3 procedure is not applicable to very large or very leaky buildings where the building pressure cannot be easily controlled. In addition, the pressure control method does not eliminate the spatial variability of VOC concentrations that is observed at many investigation sites. At some sites, this spatial variability can make interpretation of the monitoring results more difficult. Results showing that VI occurs only under depressurized conditions will not be directly applicable to normal building operating conditions because the observed magnitude of VI under these conditions may be greater than under normal operating conditions. In these cases, the investigator may choose either preemptive mitigation or continued monitoring.

Regulatory Acceptance: The Tier 3 investigation procedure was evaluated and verified through the USEPA Environmental Technology Verification (ETV) program (Battelle, 2011). An article describing the method and results has been published in the Environmental Science and Technology Journal (McHugh et al., 2012).

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APPENDIX A

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